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Chapter

# Long-Distance Wireless Power Transfer Based on Time Reversal Technique

Bin-Jie Hu, Zhi-Wu Lin and Peng Liao

## Abstract

Wireless power transfer (WPT) using microwave irradiation can set human free from the annoying wires. However, WPT has low energy efficiency due to electromagnetic wave diffraction in the case of indoor non-line-of-sight (NLOS) and causes electromagnetic radiation pollution around the room in the case of indoor line-of-sight (LOS). Time reversal (TR) technique is an inverse operation of timedomain signals and makes full use of the multipath effect. TR technique can improve the efficiency and reduce the pollution due to its unique temporal–spatial focusing effect. We will detail the principles of TR with the finite TR arrays. What's more, we propose a sequential convex programming (SCP) algorithm based on diode circuit to obtain the optimal frequency point amplitude to further improve energy efficiency. The simulation result shows that the TR-SCP-WPT system model will get the significant energy gain.

Keywords: wireless power transfer, time reversal, sequential convex programming

#### 1. Introduction

With the development of economy and science technology, more and more applications of wireless electronic products have been made. People have higher requirements on power transmission mode, efficiency, security, and so on. The traditional battery supply mode limits the using time of electronic products. However, reducing energy consumption or increasing battery capacity is not the most essential solutions to which. The wired cable power supply method is also not suitable for communication electronic products with strong mobility and wide distribution. Therefore, wireless power transfer (WPT) is a trend.

There are four types of WPT: magnetic induction coupling, magnetic coupling resonance, laser, and microwave. Among them, microwave power transmission has a bright prospect, since it is not limited by distance and it does not require a precise angle [1]. But WPT has low energy efficiency due to electromagnetic wave diffraction in the case of indoor non-line-of-sight (NLOS) and causes electromagnetic radiation pollution around the room in the case of indoor line-of-sight (LOS). The transmission efficiency of microwave power transmission is mainly composed of three parts: microwave and direct current (DC) conversion efficiency, antenna receiving efficiency, and electromagnetic wave spatial transmission efficiency.

Time reversal (TR) technique is an inverse operation of time-domain signals and makes full use of the multipath effect, which can improve the efficiency by the

temporal effect and reduce the pollution by the spatial effect. In [2], it conducted a TR indoor experiment with a nanosecond pulse with a carrier frequency of 2.45 GHz. It is proven that TR can achieve an energy gain of 30 dB, and when continuous wave is used, the TR scheme can avoid indoor fading phenomenon. In [3], it explores the spatial profile of TR-WPT for energy reception at the vertical direction of the focus point in a metal cavity and gives a closed-form expression. In [4], it uses the temporal–spatial focusing effect of TR, combined with coils containing metamaterials, to illuminate centimeter-level LED lamps, thus demonstrating the precise control of near-field electromagnetic waves.

TR can improve the transmission efficiency, and we also consider the microwave and DC conversion efficiency. The conversion efficiency depends on rectenna. It is not only a function of rectenna design but also a function of input waveform, i.e., input power and shape. This results in that the conversion efficiency is not a constant, but a nonlinear function of the input waveform [5]. Therefore, we consider a nonlinear rectenna circuit model in our system model with TR technique. Then we propose a sequential convex programming (SCP) to get the optimal frequency amplitude for the better conversion efficiency.

The potential of TR and SCP to handle efficiency issues for WPT systems is investigated in this chapter. We introduce the background of WPT and TR in section 1. Then we detail the principles of TR in section 2. We describe the TR-SCP-WPT system model in section 3. Finally, the energy efficiency performance of the WPT system is proposed.

#### 2. Principles of TR

Time reversal is a digital signal processing technique. If applied to waveform design, it can be used as a beamforming technique. According to Fink's time reversal cavity (TRC) in [6], the time reversal technique uses the detection signal to obtain all the information of the spatial channel so that the source signal can be perfectly reconstructed in the original position. Considering the actual situation, Fink uses the Huygens principle to transform the three-dimensional TRC into a two-dimensional and finite number of time reversal mirrors (TRM). The basic idea of time reversal technique is to reverse the signal in the time domain or phase-conjugate the signal in the frequency domain. The process of TR contains two stages as shown in **Figure 1**. The first stage is detection stage. The source transmits the



**Figure 1.** *The process of TR (a) detection stage (b) TR stage.* 

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An illustration of TR (a) the channel probing phase and (b) the data transmission and focusing phase [7].

detection signal. In the second stage, TR stage, TRC records the signal with the channel impulse response (CIR) and then reverses it. The time reversal signal will arrive at the same position of the source through the same CIR.

The CIR goes through by the multipaths. To more detail, let us imagine that there are two points A and B in the space of the metal box like in **Figure 2**. When A transmits radio signals, its radio waves bounce back and forth in the box. Some of them bounce back and forth through B. After a period of time, the energy level decreases and can no longer be observed. Meanwhile, B can record the multipath distribution of arrival wave as time distribution. Then, such multipath distribution is inverted (and conjugated) by B and emitted accordingly, the last one and the last one. Through channel reciprocity, all waves following the original path will arrive at A at the same specific time and add up in a perfect and constructive way. This is called focusing effect [7] (**Figure 2**).

The specific operation of TR is to reverse the time-domain signal on the time axis or to adopt phase conjugation for the complex frequency domain signal. In our research, we choose the operation in time domain.

#### 2.1 Temporal focusing effect of TR

The temporal–spatial focusing effect of TR utilizes the principle of channel reciprocity, which means that in the two stages, the channel information is time invariant. Channel reciprocity requires a high correlation between the CIR of the forward link and the backward link, while channel stability requires that the CIR be stationary for at least one of the detection and TR stages. Experiments in the laboratory area show that the correlation of CIR between forward and backward links is as high as 0.98 in [8]. Therefore, TR can play an important role. The temporal focusing effect of TR refers to that the signal originally arriving last will be transmitted first while the signal originally arriving first will be transmitted last, and finally the signal of all paths arrive at the same moment.

We consider a long distance and wireless environment, namely, rich multipath channel can be represented as

$$h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l)$$
(1)

where L is the whole number of multipath,  $a_l$  is the amplitude of the path,  $\tau_l$  is the delay of the path, and  $\delta()$  is the Dirichlet function.

According to the process of TR, the TR signal containing the reversed CIR will go through the same CIR. Therefore, there is an equivalent channel of TR, such as

$$h_{eq}(t) = h(-t) \otimes h(t)$$

$$= \sum_{l=0}^{L-1} \alpha_l \delta(-t - \tau_l) \otimes \sum_{k=0}^{L-1} \alpha_k \delta(t - \tau_k)$$

$$= \sum_{l=0}^{L-1} \sum_{k=0}^{L-1} \alpha_l \alpha_k \delta(t - (\tau_l - \tau_k)) \qquad (2)$$

$$= \sum_{l=0}^{L-1} \alpha_l^2 \delta(t) + \sum_{l=0}^{L-1} \sum_{k=0, \ k \neq l}^{L-1} \alpha_l \alpha_k \delta(t - (\tau_l - \tau_k))$$

$$= A_{focuse} + A_{sidelobe}$$

According to Eq. (2), the equivalent channel is focused to zero moment and is superposed by L paths. In addition, this will generate a lot of sidelobe information as  $A_{sidelobe}$ . Since the multipath delay range is large and the difference of  $(\tau_l - \tau_k)$  is the same, the equivalent channel has many smaller side lobes on the time axis. We prove the temporal focusing effect of TR by the indoor channel, IEEE802.15.3a in [9] like in **Figure 3**.

According to Eq. (2), at zero-focus moment, the effect of delay is just offset, and the L multipath components add up, resulting in an increase in peak value at that time. **Figure 3a** shows the normalized indoor channel, and the TR equivalent channel of **Figure 3b** is time reversed by the channel of **Figure 3a**. It can be seen from the peaks of the two that the TR equivalent channel has an order of amplitude higher than the peak, which is consistent with Eq. (2). Multipath delays can cause phase shifts in the signal. Therefore, for the transmitted signal, it is equivalent to the fact that at the time of focusing, the signal information is superimposed in phase, and a focus peak appears. This is the temporal focusing effect of the TR.



Figure 3. Temporal focusing effect of TR (a) CIR (b) TR channel.

#### 2.2 Spatial focusing effect of TR

The spatial focusing effect is illustrated by the time reversal simulation experiment in a reverberant metal cavity through the XFDTD. As shown in **Figure 4**, there is the source node A at the center of reverberant metal cavity (0, 0, and 0 mm) and four time reversal mirror (TRM) array elements namely TRM1 Long-Distance Wireless Power Transfer Based on Time Reversal Technique DOI: http://dx.doi.org/10.5772/intechopen.89078



(200, 0, and 0 mm), TRM2 (-200, 0, and 0 mm), TRM3 (0, 200, and 0 mm), TRM4 (0, -200, and 0 mm). The distance between the source node A and the TRM array elements is 200 mm, which is in the far field(  $L > \lambda$ ,  $\lambda$  is the component of the signal included the shortest wavelength).

The basic TR process in this reverberant metal cavity proceeds as follows: first, the detection signal x(t) is injected into the cavity at the source node A, and the received signal at point B of the TRM array element is y(t) after passing through the channel  $h_{AB}(t)$ :

$$y(t) = x(t) \otimes h_{AB}(t) \tag{3}$$

where  $\otimes$  represents the convolution. Second, the received signal y(t) is time reversed at point B and injected into the cavity again. The received signal at point A of source node is as follows:

$$R_A(t) = y(-t) \otimes h_{BA}(t)$$

$$= x(-t) \otimes h_{AB}(-t) \otimes h_{BA}(t)$$

$$= x(-t) \otimes h_{eq}(t)$$
(4)

where  $h_{eq}(t)$  is an autocorrelation function of  $h_{AB}(t)$ , which can be regarded as the equivalent channel impulse response of TR.

When the channel impulse response between point C (at a certain distance from point source node A) and point B of TRM array unit is recorded as  $h_{BC}(t)$ , the expression of received signal at non-source node can be obtained as follows:

$$R_{C}(t) = y(-t) \otimes h_{BC}(t)$$

$$= x(-t) \otimes h_{AB}(-t) \otimes h_{BC}(t)$$
(5)

Because of the maximum value range of coherent superposition of multipath signals, the spatial focusing effect of TR can make the multipath signals superpose coherently at the source node A at a certain time, thus enhancing the electric field intensity at the source node to produce a peak. As shown in **Figure 5**, it can be seen that TR processing results in a lower signal amplitude in an area other than the location of the source node and the recovery of x(t) occurs at the primary source node A, and the peak value of  $R_A(t)$  is higher than the peak value of  $R_C(t)$ . Because  $h_{AB}(-t)$  and  $h_{BC}(t)$  are non-autocorrelation, there will be coherent cancelation in the signal. The obtained  $R_C(t)$  and x(t) signals are completely different. The peak power ratio of the signal that the source node and the non-source node can receive is determined by the total multipath gain of the channel and the correlation



#### Figure 5.

Spatial focusing effect of time reversal electromagnetic wave: Electric field distribution Z = 0 plane of the source node (a) in NO-TR system (b) in TR-WPT system.

coefficient between the channels. Even if the multipath gain of the source node and the non-source node is the same or slightly higher, the ratio of peak power will still have a large gap when the channel correlation coefficient is very small. In the scattering-rich environment, as long as the distance is enough, the correlation of impulse response of multipath channel decreases to a very low level. The spatial focusing effect of TR is adaptive and can reduce electromagnetic radiation pollution.

#### 3. WPT system model and analysis

Through section 2, we can get the idea that TR technique can increase power gain by the temporal focusing effect and reduce the electromagnetic radiation pollution by the spatial focusing effect. In WPT system, the important part is the rectifier antenna. According to [5, 10], the rectifier antenna consists of a diode and a low-pass filter to transform radio frequency (RF) input signal into direct current (DC). The collected DC energy is a function of input power level and RF-DC conversion efficiency. RF-DC conversion efficiency is not only a function of rectifier antenna design but also a function of input waveform, that is, input power and shape. Therefore, we consider to design the frequency point amplitude to improve energy efficiency based on the diode circuit with TR technique.

#### 3.1 System model

Through the above introduction, we consider the system model as **Figure 6**. Because the two stages of TR, the transmitter and receiver both have two antennas. In the transmitter, the channel estimation module can extract the channel state information (CSI) between two devices. Then the time reversal module can use the CSI to obtain the time reversal signal. According to the rectenna circuit model, a non-convex problem about the received signal and the output voltage can be extracted. Usually, a non-convex problem should be converted into a convex problem [11]. We propose that the sequential convex programming algorithm can solve the problem. More detail can be found in [12] due to the space limitations. Finally, the sequential convex programming module will get the optimal frequency point amplitude according to rectenna circuit.

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#### 3.2 Simulation

Firstly, we consider a multipath channel response based on a metal cavity like in **Figure 7**, with the measurement in frequency domain by Vector Network Analyzer (VNA) [13].

In [14], it proposes that the larger the bandwidth, the more the number of multipath like in **Figure 8**. In the above analysis and Eq. (2), the performance of TR is related to the multipath. In addition, the factor of SCP is frequency point numbers. Therefore, we compare three system models, namely, direct transmission (DT), TR, and TR-SCP, in different bandwidth (20–200 MHz) and frequency point numbers (2–8).

## 3.3 Result and analysis

In the simulation, we set the carrier frequency as 5.8GHz and the emitting power as 36 dBm. Then we combine the measured channel with Matlab module like in **Figure 6** to perform the experiment. As in **Figure 9a**, the TR-SCP and TR systems perform much better than the DT system because the TR technique can take





**Figure 7.** *The metal cavity.* 



#### Figure 8.

Percentage of captured energy versus the number of significant eigenvalues with a single antenna [14].



**Figure 9.** *Result of the simulation (a) power and bandwidth (b) power and frequency points.* 

advantage of the multipath channel. What's more, as the bandwidth becomes bigger, their performance is better. As in **Figure 9b**, because the TR-SCP can make use of CSI based on the diode circuit, its performance will be better than TR system. And when the number of frequency point is from 2 to 8, the system can get more information about CSI. Therefore, in **Figure 9b**, the TR-SCP system will be better and better than the TR system as the number increases.

### 4. Conclusion

This chapter firstly introduces the principle of TR technique. Then according to the focusing effect of TR, we propose TR be applied to WPT. Because the conversion efficiency is associated with the waveform, we propose SCP algorithm based on diode circuit to design the amplitude of the emitting signal. Finally, we combine the SCP with the TR to propose a SCP-TR system model. Based on the results of the simulation, our design model can achieve better performance on wireless power transmission. Therefore, we believe that our model is robust and stable in a complex

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and rich multipath environment and can adapt to a variety of wireless power transmission scenarios.

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